SPARROW: A Steam Propelled Autonomous Retrieval Robot for Ocean Worlds

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Abstract— **This paper presents the results of a NIAC Phase I study into the use of a propulsively hopping robot for the exploration of Europa's rugged, icy surface. Named the "Steam Propelled Retrieval Robot for Ocean Worlds," SPARROW is a multi-thruster robot passively gimballed within a protective, spherical shell, which enables it to freely rotate, self-right, and tumble over chaotic terrains. SPARROW is envisioned as a soccer ball-sized payload to a primary lander mission. Europa's abundant surface ice would be harvested as an in situ propellant source. The principal objective of SPARROW would be to increase the science return of a Europa landed asset by enabling access to distal, spatially distributed geologic units.**

The design of mobility systems for Europa is challenging, due in part to its almost entirely unconstrained surface topography and strength. Images returned by Voyager and Galileo yielded resolutions on the order of hundreds of meters per pixel, with localized regions reaching 6 meters per pixel—still far larger than a typical rover. A key benefit of SPARROW's hopping, impact-tolerant design, is that it eliminates the need for *a priori* information on the terrain topography and surface strength; no surface reaction forces are required for motion. In this context, SPARROW is entirely terrain agnostic.

In this paper we detail the results of three study objectives: i) to quantify the energy required to collect surface ice, change its phase, and maintain propellant temperature, ii) to identify control and estimation strategies that enable SPARROW to successfully reach, and return from, regions of scientific interest, and iii) to characterize the impact of SPARROW's range on likely science return. Five water-based propellant architectures are presented alongside their mass, power, and volume requirements. Monte Carlo simulations of SPARROW hopping and tumbling over 1 km of glacial ice are summarized, characterizing SPARROW's sensitivity to uncertainty in: initial conditions, thrust control, and cage-terrain interaction. Finally, a science traceability matrix is presented, which details the effect of sortie range on three science goals: constraining Europa's evolutionary morphology, assessing sub-surface ocean habitability, and searching for life and/or biosignatures.

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1. INTRODUCTION

The Steam Propelled Autonomous Retrieval Robot for Ocean Worlds (SPARROW), shown in Figure 1, is a collaborative, NIAC Phase I study, between NASA's Jet Propulsion Laboratory, Purdue University and Honeybee Robotics. Envisioned as a soccer ball-sized payload to a primary lander mission, SPARROW is a propulsively hopping robot, enabling rapid access to spatially distributed regions of scientific interest. The principal advantage of SPARROW is its terrain agnosticism; its design and operation requires no *a priori* knowledge of terrain topography or strength. In this paper the concept, mission architecture, and fundamental feasibility of SPARROW are addressed. Considerations for propulsion, energetics, controls, localization, and science operations are described.

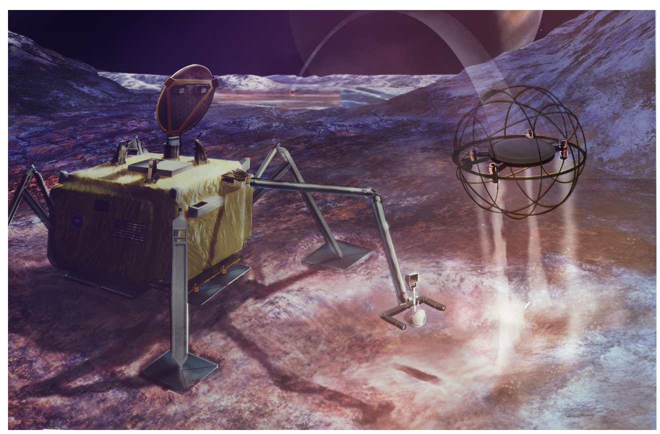

Figure 1. **Artists conception of SPARROW leaving its mothercraft. Adapted from [ea16]**

Science Background

Images of Europa's surface from the Galileo spacecraft reveal multiple feature types and geologic units, each with a distinct morphology and discoloration thought to be related both to composition and formation mechanism [Zac18]. These features provide clues as to how material is transported from Europa's subsurface ocean to the surface. Identification of mineral species and biomarkers in these regions is likely to hold significant implications for Europa's biological potential, history, and subsurface habitability, as referenced in the Decadal Survey [ea11].

Multiple models exist for the formation of various geologic units on Europa's surface, and as yet there is no scientific consensus on which feature types are the most compelling for future exploration. Scientific considerations for landing site selection include the inferred composition and abundance of non-ice materials, the potential for surface-subsurface exchange, and the desire to land at a relatively young, unprocessed surface location. Landing site selection is further complicated by the fundamental tradeoff between the safety of the landed asset and the potential for enabling discovery. Accordingly, selection of a safe landing site for an immobile asset may be balanced against the capabilities of a mobile payload to reach distal regions of greater scientific interest. It is the scientific premise of the SPARROW concept that the enablement of multi-site, multi-geologic unit exploration holds the potential to greatly increase the science return while reducing the risks associated with landing at a less compelling site.

Science Return as a Function of Mobility

The exploration of solar system bodies, such as Earth's moon and Mars, has often followed the model of high-coverage remote sensing missions preceding closer inspection via surface *in situ* operations, first with static landers and successively with mobile assets. NASA has historically staged missions within this model to mitigate the complexity of designing spacecraft in the face of uncertainty about the target operating environment; data collected in early missions can be used to impact the design of higher complexity downstream missions that return to the target body.

In recent years, Ocean Worlds have garnered substantial interest from the scientific community, precipitating the Europa Clipper mission and Europa Lander study. If NASA's exploration of Ocean Worlds proceeds in family with the lunar and Martian exploration paradigms, a subsequent surface mobility mission to Europa is a possibility. However, the travel time to Europa is significantly longer than to Mars, and between the present day and the arrival of Clipper (mid to late 2020s), further measurements of Europa's surface will not become available. As such, mission concepts that are inherently robust to terrain uncertainties are advantageous.

Mobility offers many advantages to Europan exploration, including the ability to access topographically extreme regions and to enable science outside of the potentially exhaust contaminated landing zone. Figure 2, adapted from [Dog07], reveals the heterogeneous distribution of geologic units across Europa's surface. Chaos, ridges, bands, and heavily disrupted plains are among its features. Three mobility length scales are emergent:

1. Local mobility (0–1 km) within one geologic unit
2. Medium-range mobility (1–10 km) enabling a partial transect of one geologic unit
3. Long-range mobility ($\geq$ 10 km) enabling measurements to be made across multiple geologic units

An example bounding box of side-length 100 km is highlighted in Figure 2, shown as being capable of reaching four units. While terrain closer to the interior of a geologic unit is likely younger and may represent freshly upwelled material, the outer reaches are likely to have been formed at the feature's inception. In this scenario, a partial or full transect would interrogate the historical record of the feature, subsuming both age and possible means of formation. Moreover, mobility across multiple geologic units enables selection between multiple hypotheses through comparison of the historical records for each geologic unit and interrogation of the relationships between them. In this manner, the ability to reach multiple units holds the significant advantage of providing relational insights over a broader range of Europa's surface features. Despite its potential for dramatically increasing science return, surface mobility on Europa is not without significant technical challenges, which are detailed in the following section.

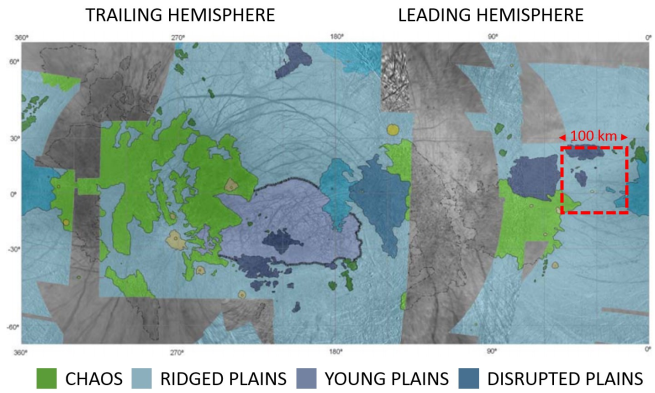

Figure 2. Distribution of geologic units across Europa's surface. Adapted from [Dog07]

2. Environmental and Terrain-Based Challenges to Mobility

Europa presents challenges to surface mobility that can be broadly grouped into two categories: environment and terrain. Owing to its position within the Jovian radiation environment, Europa's surface is exposed to significant ionizing radiation, largely in the form of electrons [PCG+09]. Within its expected 20 day surface mission, the proposed Europa Lander is anticipated to be exposed to a total ionizing dose of approximately 1.7 Mrad [ea16]. This is far in excess of that experienced by previous and current Martian robotic explorers. While some of this dose may be mitigated through the use of shielding and hardening, Europa's radiation environment remains extreme. In the context of a relatively short mission (weeks) and the spacing of scientifically compelling sites, the requirement for *rapid* mobility becomes evident.

Rapid surface mobility on other worlds is challenging for several reasons, including the need for robustness to terrain uncertainty, the necessity of (perhaps fully) autonomous operations, and mitigation of multiple sources of risk. Uncertainty surrounding terrain properties and topography can readily lead to complex robot-ground interactions that are difficult to predict. Images of Europa taken by Voyager and Galileo have resolutions on the order of hundreds of meters per pixel, with localized regions reaching 6 meters per pixel. Such resolution does not provide sufficient knowledge of terrain features at the lander/robot scale to inform designs of terrain-dependent mobility systems.

In addition to topographic challenges at Europa, there currently exist no means of remotely determining surface strength, which dictates both the traction of a wheel (or foot) and the extent to which it will sink into a regolith – a critical and often limiting factor in the efficacy of mobility systems. Surface strength is a function of both the material and the weathering processes to which it is exposed. On Europa, surface ice is subject to multiple regolith-producing forces: tectonics, micrometeoroid bombardment, charged particle impacts, and the possibility of plume ejecta deposition [MBB+09]. Although past measurements have penetrated only the remote sensing layer (up to ≈10 wavelengths), they are in agreement with a highly porous, unconsolidated surface. Photometric and thermal inertia measurements made by the Galileo spacecraft indicate void fractions (free space to grains) on the leading and trailing sides on the order of 0.25 and 0.79, respectively [BG88]. Regolith grain sizes in the range of 20 to several hundreds of microns have been reported [ea05], and the surface thermal inertia is 20 times lower than the value expected for solid water ice [Mor05]. The true strength of this surface and its topography will not be known prior to the first landing.

3. The SPARROW Mission Concept

In the face of significant uncertainty surrounding terrain properties, it is prudent to ask how one can reasonably defend the efficacy of a proposed mobility system design. Myriad mobility concepts exist as variations of wheeled, tracked, and legged systems. All, however, rely on *a priori* knowledge of the surface they are intended to traverse. A promising alternative to more traditional ground-based mobility architectures is that of a hopper. Hoppers holds the distinct advantage of minimizing time spent in contact with the terrain. However, conventional mechanical hoppers rely on a relatively strong terrain on which to impart reactive forces and are, thus, terrain-dependent. In the possible case of a weak, loose regolith, such mechanisms may be inefficient or fail. Inspired by the HyTAQ [KS14] and GimBall (Figure 3) [FW15] robots, SPARROW features a central module passively gimballed inside a protective, spherical shell. Contrary to the use case for HyTAQ and GimBall, Europa's lack of an atmosphere precludes the use of rotor flight. Rather, SPARROW replaces the quadrotors with a thruster configuration, enabling it to operate in a vacuum environment. A key innovation of the SPARROW concept is the use of a propellant harvested from an abundantly available in situ material: water ice. Water-based propellants are not unusual for low-thrust applications [JBF+17] [RJC+18].

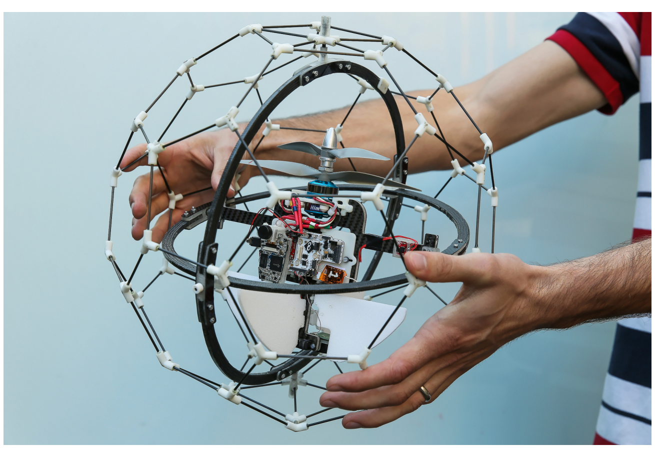

Figure 3. The Gimball robot [FW15]

With the primary lander as SPARROW's base, ice (propellant) extraction from Europa's surface is performed through the incorporation of Honeybee Robotics' Europa Drum Sampler into the lander arm. Akin to SPARROW's terrain agnosticism, EDuS' ice harvesting capabilities are independent of surface roughness. Its rotating cutter head throws shavings behind a buffer plate, which when inverted, deposits the ice into the heating chamber through a funnel. Figure 4 depicts the key components of EDuS' design.

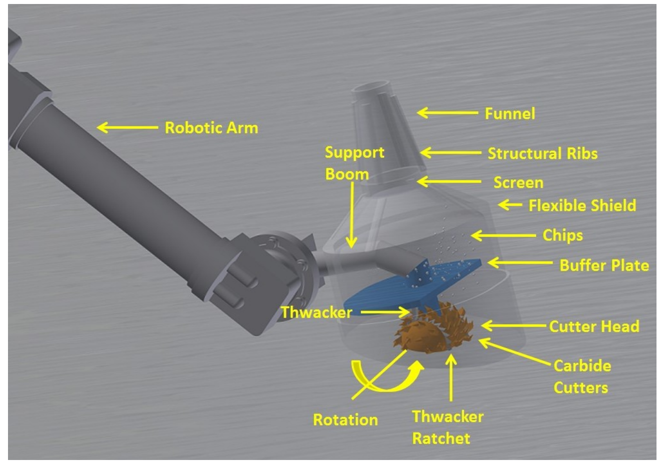

Figure 4. The Europa Drum Sampler (EDuS) major components

As illustrated in Figure 5 and expanded upon here, there are several phases of SPARROW's operation, which may be repeated throughout its mission:

1. The lander arm, equipped with the EDuS ice collector, is deployed to the surface. The requisite mass of ice is acquired, melted, and transferred to SPARROW.
2. The ice is converted into propellant in one of the following forms discussed in Section 5: Superheated steam, hot water, cold water, resistojet, or a hydrogen plus oxygen bi-propellant.
3. SPARROW is released by the lander arm and pulses its thrusters to roll away from the lander, clearing any potential collision zone.
4. Once clear, SPARROW orients itself in the direction of the first target site and briefly exhausts steam through its nozzles, putting it on a ballistic arc to the target.
5. SPARROW makes an uncontrolled landing at the remote geologic target. Being able to freely rotate within its protective shell, SPARROW comes to rest at an orientation amenable to measurement or sampling activities.
6. With the measurement complete, SPARROW uses its remaining propellant to hop back to the lander, making a controlled landing at a safe standoff. Pulsing its thrusters, SPARROW maneuvers itself to within the lander arm's reach for re-capture and sample/data transfer.

4. Study Objectives and Findings

This study has focused on three facets of the mission architecture that require in-depth feasibility analyses:

1. (Energetics): Quantify the energy required to collect surface ice, change its phase, and maintain propellant temperature
2. (Controllability and Localization): Identify control and estimation strategies that enable SPARROW to successfully reach, and return from, regions of scientific interest
3. (Science Operations): Characterize the impact of science payload capabilities on system sizing transfer.

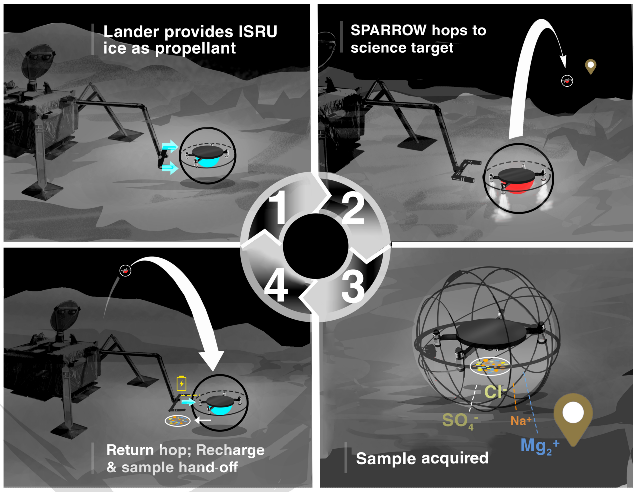

Figure 5. **SPARROW concept of operation**

As with many NASA mission, science return is the primary motivation for the SPARROW concept. Likely science return as a function of SPARROW's capabilities is used to drive system-level requirements. As such, the Science Operations objective is discussed first in subsection 4.

Science Operations

This subsection details the science traceability matrix (STM) and instrument-types considered under this task. The objective of the STM is to drive engineering requirements toward those that maximize SPARROW's science potential while maintaining feasibility. Here we present a distillation of the STM, the shares the goals and objectives of the 2016 Europa Lander Study report [ea16] and is augmented to highlight the effect of mobility. At the highest level, the STM's three goals are:

1. **Biosignatures**: To search for evidence of life, past or present, on Europa.
2. **Habitability**: To assess the habitability of Europa via *in situ* techniques.
3. **Geophysics**: To characterize surface morphological and geophysical properties.

Goals and Objectives

Goal 1 (Biosignatures): There is no single, conclusive test for the presence of life. However, when considered as a biosignature-collective, organic, inorganic, and morphological indicators may be used to *suggest* the presence of life. Biosignatures include, but are not limited to: patterns among molecules (e.g., carboxylic and amino acids), cell-like structures, surface discoloration, and biominerals such as SiO_2. Spatial variation in the detected number and type of biosignatures is highly likely. As such, multi-site measurements would increase both the probability of biosignature detection. Comparisons among multiple organic indicators at different locations would enable the evaluation of diversity of life on Europa, past or present. The four objectives of Goal 1, as reported in [ea16] are:

1. To detect and characterize any organic indicators.
2. To identify and characterize morphological and textural indicators of life.
3. To detect and characterize inorganic indicators.
4. To determine the provenance of material, either sampled or measured.

Goal 2 (Habitability): Whether or not Europa reveals evidence of life, the assessment of regional habitability is important. Habitability may by assessed by studying the composition of non-ice species and measuring their proximity to liquid water and/or recently-erupted material. In similarity with Goal 1, the probability of identifying varied surface compositions and enabling access to plume material increases proportionally with sortie range. The three principal objectives satisfying Goal 2 are:

1. To characterize the non-ice composition of Europa's near-surface material and determine whether there are indicators of chemical disequilibria essential for life.
2. To determine regional surface proximity to liquid water and recently erupted materials.
3. To determine habitability across multiple geologic units and feature types.

Goal 3 (Geophysics): Studying the physical properties of Europa's surface and the dynamic processes that modify it would provide important context to any biosignature indicators or habitability analyses. In addition to surface measurements, Goal 3 seeks to identify the depth of the subsurface ocean as a function of surface location. The greater SPARROW's range, the better this can be constrained through the use of a sounding package. The objectives of Goal 3 are:

1. To observe the properties of surface and near-subsurface materials
2. To connect ground-truth morphological observations to those made by remote assets (e.g., Clipper, Galileo).
3. To characterize exogenous and endogenous dynamic processes and their effects on Europa's surface physiochemistry.

As discussed in the introduction, the potential for scientific discovery increases monotonically with sortie range. The present uncertainty surrounding Europa's surface properties, as well as the undetermined choice of landing site, make an *a priori* quantification of this potential intractable. In this paper we use three example length scales in order to facilitate a discussion of the effects of SPARROW's capabilities on science return. The sortie ranges,*L*, considered are: $1\,km$, $10\,km$, and $100,km$. All three length scales hold common advantages over a static asset. These are enumerated below, proceeded by a discussion of science return as a function of length scale. All length scales:

1. Greatly increase the sampling and/or measurement area surrounding the lander.
2. Reduce the risk of being constrained within a less scientifically compelling region or anomalous workspace.
3. Enable measurements well beyond the anticipated lander-exhaust contamination zone.

At a 1 km sortie range, SPARROW would enable a partial analysis of one geologic unit or limited interrogation of two units. A partial study would yield a comprehensive understanding of the compositional range of materials contained in a single unit, their relative abundance, and potential for preserving biosignatures. Small variations in dynamic processes may also be observed. Alternatively, two geologic units could be sparsely sampled (e.g., a band and chaos), alleviating some concern surrounding the choice of landing site and enabling comparisons of subsurface ocean depth. Two units would likely exhibit very different characteristics and hold varied potential for biosignature detection and habitability analyses. Further, a 1km range may allow access to nearby plume deposits (if present) or recently-formed features due to the proximity to liquid water.

At a 10 km sortie range, a full transect of a single unit or partial transects of two units are possible. Access to multiple unit contacts is likely, and may improve our understanding of the stratigraphic relationships among units. Unit thicknesses, ages, and chemical concentrations may all be interrogated to determine likely material provenance.

At up to 100 km sortie range, full transects of up to two units may be possible. Such transects would enable observations to be made of very different terrain types, greatly increasing the opportunity to observe disparate compositional characteristics. A 100 km sortie range also greatly increases the utility of a seismometry payload, allowing ocean depth as a function of surface location to be much better constrained. The geologic histories and surface modifications, both in morphology and chemistry, could be studied. Sparse sampling of up to four units may also be possible at 100 km, significantly decreasing the risk of landing at a less compelling site and increasing the chance of biosignature detection.

Science Package

This subsection provides a brief discussion of potential SPARROW science packages. It should be noted that a complete assessment of all instrument options is yet to be completed. As such, two example point designs are discussed: threshold and baseline. Threshold is defined as the minimal set of instruments to warrant flight of the SPARROW concept, whereas baseline would represent a more complete set yielding higher science return. The threshold instrument package is proposed as that of a context remote imager and spectral imager. The baseline package would include a context remote imager, microscopic imager, seismic package, and compositional spectrometer. Context remote imagers, such as the Mars Science Laboratory (MSL) navigation cameras (NCAM) provide ground-truth, which may be used to refine data/images obtained by more remote assets such as Europa Clipper. They may also provide information regarding the provenance of deposited material and the detection of plume vents not visible from the static lander. Spectral imagers, such as the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) or MSL's MastCam (MCAM) would enable the detection of various minerals via the use of lens filters. This may result, as has been the case for CRISM, in the selection of scientifically compelling regions for future operational planning. Microscopic imagers, such as MSL's Mars Hand Lens Imager (MAHLI) would enable the detection of small-scale surface properties. On Mars, such instruments are used to examine the micro-structure of rocks and regolith, which in the context of Europa would be used to refine our knowledge of surface mechanical properties. Microscopic imagers may also be able to observe cell-like structures, if present. A seismic package, such as the Geophysical Sounding System (GSS) is a broad-band seismometer and would likely be used in the context of determining ocean depth from the surface. Under the SPARROW mission concept, it is conceivable that a GSS-like instrument could be used to interrogate ocean depth as a function of surface location. This would require SPARROW either to maintain its location for 3.5 days (one Europan tidal cycle) or to deposit several seismometers across the surface. An imaging spectrometer represents an interesting and compelling option for mobile, Europan exploration. Imaging spectrometers such as the Mars 2020 mission's SHERLOC instrument or MSL's CCAM hold the ability to perform organics detection. Further, if the imaging spectroscopy is performed following a laser-induced ablation of the surface, as is the case for CCAM, it is possible that much of the top, irradiated layer, may be able to be removed by the laser prior to initializing the measurement. This represents an interesting technique enabling shallow-subsurface access beyond the approximately 10 cm irradiated layer [NHP18].

5. Propellant Extraction, Propulsion, and Energetics

The extraction of ice, its conversion to propellant, and maintenance of propellant temperature are key feasibility considerations of this study. Europa's surface temperature seldom exceeds 100 K [Ash16] while peak solar power reaches only about 50 W/m^2 [LCN]. The energy required to operate SPARROW, being too small to accommodate a large solar array, would necessitate the use of batteries and/or a radioisotope power source. Much of SPARROW's required energy is thermal, making the heat from plutonium-238 inside a general purpose heat source (GPHS) module a viable and efficient means of heating the ice. A typical GHPS can provide 250 W of continuous thermal power at a volume of only 5×10^{-4} m^3 and a mass of 1.5 kg [Dud].

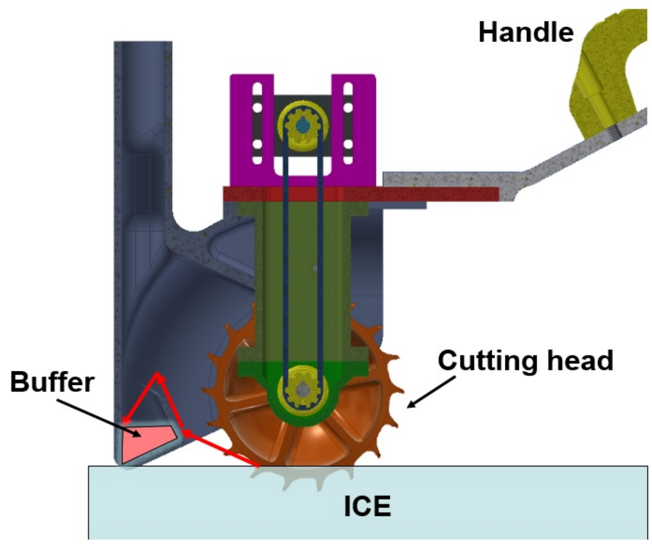

Figure 6. Design of EDuS proptype to be mounted on KUKA arm.

The extraction of ice is conceived as being performed by the Honeybee Robotics Europa Drum Sampler (EDuS) [CCD+09]. As shown in Figure 4, EDuS is comprised of a rotating cutter head and thwacker ratchet, which can be applied to the surface at a broad range of normal loads. The cutting head *throws* ice shavings behind a buffer plate, which when inverted uses gravity to feed the ice into a retaining funnel. Prior testing at Honeybee indicated that EDuS should be capable of excavating 1 kg of ice with 700 kJ of energy. In this study we aim to refine this number as a function of weight-on-bit (WOB), surface porosity, salinity, and temperature. Tests, yet to be completed, will be performed through the attachment of an EDuS to a KUKA robotic arm using the design shown in Figure 6. Power, J/kg (ice), WOB, and excavation rate will all be recorded as a function of the aforementioned ice variables. In the first half of this study a cutter head was prototyped in plastic and used to excavate pure water ice inside a -20$°C$ walk-in freezer. The results serve as proof of design concept and readiness for test maturity as shown in Figure 7.

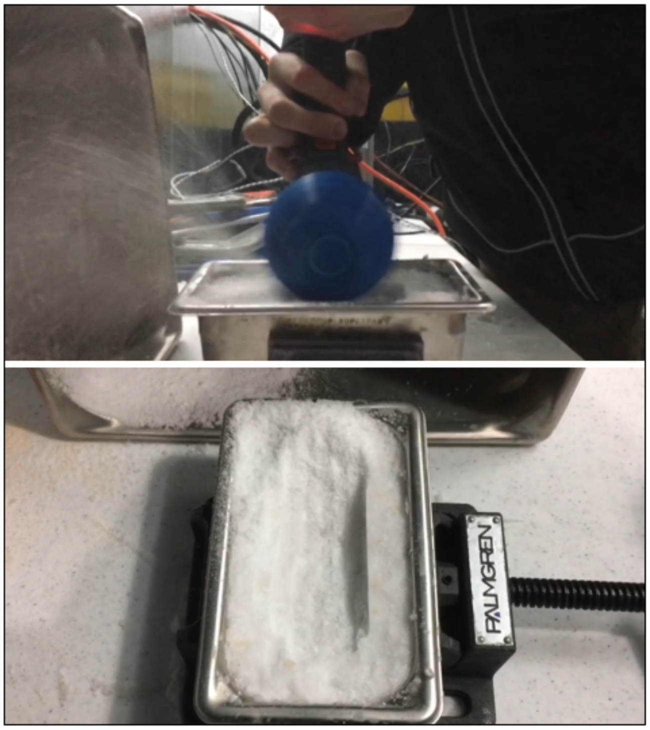

Figure 7. **Testing of EDuS printed prototype in -20C ice.**

Five SPARROW propulsion architectures were considered for use of the propellant provided by EDuS:

1. Superheated steam.
2. Hot water
3. Cold Water
4. Cold water expansion by a resistojet.
5. A hydrogen/oxygen bi-propellant separated by electrolysis.

A summary of their relative merits follows.

Superheated Steam

Superheated steam represents the simplest of the propulsion concepts considered in this task, both conceptually and mechanically. The steam, heated to approximately 1250 K would be stored inside a Hastelloy tank and exhausted through a inert-gas, blow-down, thruster. It should be noted that the choice of Hastelloy propellant tanks is ubiquitous across all propulsion systems presented here; Hastelloy has excellent thermal properties and is resistant to corrosion both by salts and sulfuric acid, both of which are believed to be pervasive across Europa's surface. Steam thrusters can achieve specific impulses on the order of 100 to 150 seconds, depending on the temperature to which the steam is heated. As a blow-down thruster, however, both thrust and specific impulse experience nonlinear reductions during firing; tank pressure and temperature cannot be maintained. As shown in Table 5, the low storage-density of steam, even at high pressures, results in the need for a large and consequently massive tank.

Hot Water

During operation of a hot-water thruster, ice/water is heated to its saturation temperature and pressure just below the critical point. One advantage of hot water over steam is its higher storage density. Upon expulsion through the nozzle the liquid experiences rapid volumetric expansion, causing it to *flash-boil*. The resulting steam produces thrust. A review of water-based thruster research found related experimental results reported by Kolditz et al [KPA$^+$04] and Sun [SW14]. These results suggest an advantage over blowdown thrusters due to the attenuation of feed pressure drop; during firing, the partially-evacuated ullage causes any remaining liquid to evaporate, thus maintaining liquid-vapor equilibrium. Kolditz et al [KPA$^+$04] showed feed pressures maintaining approximately 80% of the initial feed pressure throughout the nominal thrust duration. The calculated initial I_{SP} of hot-water thruster is similar to that of steam thrusters at the same temperature. However, hot-water thrusters have been empirically shown to experience efficiency losses due to incomplete evaporation of the water.

Cold Water

As a propellant, cold water is defined here as that which is stored slightly above its freezing point under pressure. The motivation of such a concept is to achieve the highest possible water-based propellant density in order to reduce tank volume and empty mass. Since the cold water requires a pressurant, chosen in this study to be hot water with a superheated steam head, a second, heated pressurant-tank is necessary. In general, the specific impulse of the cold water as a propellant is very low (around 20 seconds). It was found that this substantial reduction in I_{sp} outweighed the benefits of its higher storage density.

Resistojet

Resistojets utilize a heating element either to heat a cold gas or to evaporate a liquid prior to entry into the thruster nozzle. Resistojets hold the advantage of achieving high specific impulses while maintaining the propellant-density advantage of the cold water concept. Water-based resistojets have been reported on by Morren [MHHS89] and Pugmire [PSE71] as one of many possible working fluids for attitude control thrusters. Specific impulses as high or higher than steam are achievable depending on the operating temperature of the system. High thrust levels, however, are challenging to achieve due to the requirement for rapid heating at a high mass flow rate. This precipitates the need for a very high thermal power draw; ultracapacitors of sufficient capability to support SPARROW would likely range into the several tens of kilograms.

Combustion

A hydrogen plus oxygen liquid bi-propellant system represents the most complex means of propulsion studied under this task; the addition of an electrolyzer adds mass, power, and volume requirements, and bi-propellant engines are in general more complex. However, both commercial electrolyzers and hydrogen-oxygen engines are of high technology readiness level (TRL). Additionally, the specific impulses generate by bi-propellant systems can triple those of the above mono-propellant options.

In the proceeding subsection, first-order calculations regarding the likely performance of each of the propellant options are detailed. Table 5 provides a concise summary of the findings.

Propulsion Calculations

This subsection details a quantitative assessment of each propellant concept. It should be noted that these calculations are first-order, using several assumptions:

- All propellants begin as pure water ice with additional impurities.
- Thermal transfer is adiabatic and isentropic.
- Propellants behave as ideal gases inside the tank

Calculations were performed to refine estimates of the required propellant mass, tank mass and volume, and the energy consumed during propellant production (ice to viable propellant). Several sortie ranges were considered, ranging from 1 - 10 km, per the STM. For simplicity, it was assumed that burns were performed for only a small percentage of the overall hop-time along a ballistic trajectory with SPARROW's thrust vector initially aligned 45° from the horizontal. Burns were considered necessary both for initial ΔV and for a velocity reducing, but non-nulling, retro-thrust prior to landing. The required propellant mass was calculated using the ideal rocket equation. As previously noted, propellant tank mass calculations assume the use of Hastelloy (a chromium, nickel, molybdenum superalloy) as the material of choice. Tank sizing was performed assuming a spherical shape and a yield safety factor of 1.2. Tank wall thickness was calculated either as that required to hold internal pressure, or 0.05 inches, whichever was greater. The 0.05 inch minimum thickness serves to maintain structural rigidity.

The primary outcome of the results reported in Table 5 is to aid in the down-selection of propulsion strategies for further analysis with fewer idealized assumptions. It is readily observed that superheated steam is infeasible in the context of a soccer ball-sized payload; its low storage density results in a propellant tank approximately 23× the volume of the desired system. The cold-water concept is also likely infeasible due to its exceptionally low I_{SP}. The hot water and combustion concepts are both perceived as feasible at this time. Hot water holds the disadvantage of requiring a somewhat sizable tank, while the combustion option holds the highest energy requirement. A resistojet option appears attractive in the context of propulsive performance. However, the power draw required during the thrust phase is extremely high at 0.62 MW. Providing this with an electrical system is infeasible. The challenges of this power requirement may be abated by employing a thermal mass heated over time by a GPHS, however the additional mass and volume requirements are yet to be identified. Figures 8 and 9 show results for two promising candidates: hot water and $H + O$ combustion. Figure 8 compares the propellant tank mass and volume as a function of sortie range. Figure 9 represents the same sortie range but compares the differences in fueling energy for the two concepts.

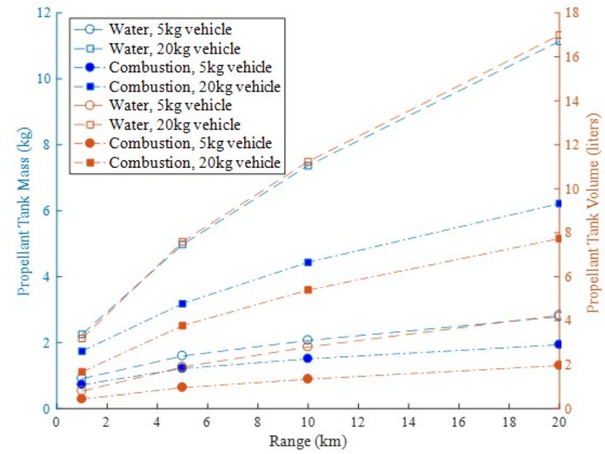

Figure 8. Comparison of propellant tank mass and volume for hot water and electrolysis-based systems

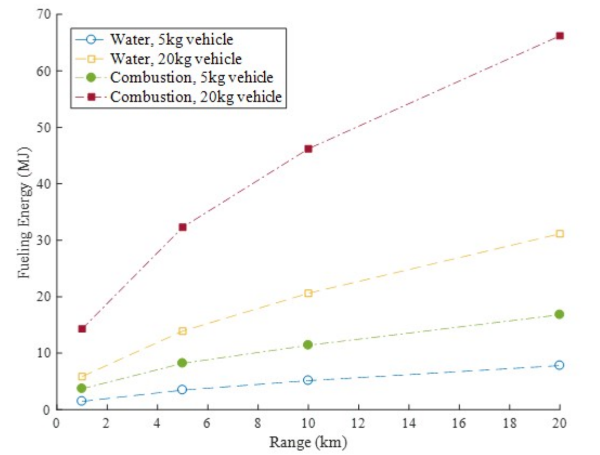

Figure 9. Comparison of fuelling energy requirements for hot water and electrolysis-based systems

6. Control and Localization

In order to simplify the hopping control and eliminate reliance on in-flight attitude control, we adopt a "point-and-shoot" hopping control, whereby SPARROW adjusts its orientation on the surface such that it is pointing along the desired hop direction, executes a single burn at maximum thrust to follow a ballistic trajectory. Additionally, we considered two potential "modes" for SPARROW's hopping control. A *direct-hop* control policy attempts to intercept the target location in a single parabolic trajectory, requiring a large initial burn for takeoff *and* one burn for soft-landing. Alternatively, a *multi-hop* control policy hops directly towards the goal, but with limited speed per hop so as to avoid the need for retro-burns (i.e., just passive landing/bouncing). The single-hop control strategy is more fuel-efficient, but it is susceptible to a mission-ending surface impact if the retro-burn fails. On the other hand, the multi-hop policy avoids this potential risk, but at the cost of poorer fuel efficiency and less tolerance to intermediate terrain roughness between the lander and target location.

While SPARROW's mobility paradigm of large ballistic trajectories is much more terrain agnostic than traditional surface mobility, it is still subject to a series of landing bounces on the largely unknown surface. Moreover, errors in hop execution (e.g., speed and direction) may induce significant trajectory variability. In order to quantify the resulting errors in landing precision and the need for subsequent corrective hops, we developed a simulation environment in which these various sources of uncertainty can be injected arbitrarily, and a large batch of Monte Carlo simulations can be run to observe the statistical variability.

As discussed in Sect. 2, terrain maps of Europa at the rover scale are not available and are unlikely to be available even prior to landing. As a Europa surface analog, we mapped a 50 m region of glaciated ice flow in Alaska, which was

Table 1. Summary of key mass, energy, and volume calculations performed for each propulsion concept.

Property	Steam	Hot Water	Cold Water	Resistojet	Combustion
Tank Pressure (MPa)	20	13	18	1.3	18
Tank Temp (K)	1250	604	630/300	1250/300	75
ISP (s)	157	77	20	191	425
Density ISP (kgs/m^3)	5520	48909	16884	191000 5	88487
Prop. Mass (kg)	4.5	10	79	3.7	1.6
Prop. Vol. (l)	129	16	94	3.7	7.5
Fueling/Firing Energy (MJ)	27	30	128	5/17	64
Tank Mass (kg)	386	11	75	1.2	5.8

used to create a 1 million-facet triangular surface mesh (see Fig. 10). While there is likely to be significant differences in the structure and geological processes between Europan and terrestrial terrain, this mesh does exhibit many features (e.g., pits and fractures) that we observe at a larger scale on Europa. Thus, for our simulations we scale this mesh up about 300x so that it better matches the resolution of our images and so that we can simulate a 1 km sortie. Surface irregularities below the facet scale are roughly captured by randomizing the surface normal upon impact.

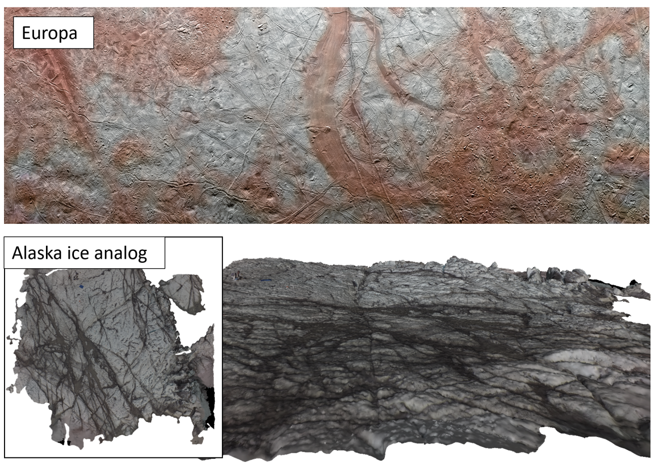

Figure 10. **Comparison of Europan surface as imaged by Galileo and the shape model of an Alaskan ice sheet used as an analog for simulations.**

Each simulation consists of a series of hops, whereby the desired hop velocity vector is recomputed based on SPARROW's position (assuming perfect estimation) relative to the target region each time the rover comes to rest on the surface. Once the target region has been reached, this process is repeated as SPARROW returns to the lander. SPARROW is modeled as a particle in a constant gravity field ($g = 1.315$ m/s^2). The initial hop velocity is randomized according to the expected control uncertainty (e.g., an unbiased Gaussian) and the rebound velocities are also randomized. For this case study, we assume a hop pointing uncertainty of 5^o (1σ), a speed uncertainty of 5% (1σ), a mean surface restitution of 0.6 with standard deviation of 0.1, and a rebound angle reflected about a randomize normal vector with $\sigma = 10^o$ about the facet normal. Also, we assume an ISP of 75 s, a dry mass of 20 kg, and a 15 m/s velocity limit for the multi-hop sorties.

The results of 1000 Monte Carlo simulations for both control policies are summarized in Fig. 11, and a few example trajectories for each policy are shown in Fig. 12. Box

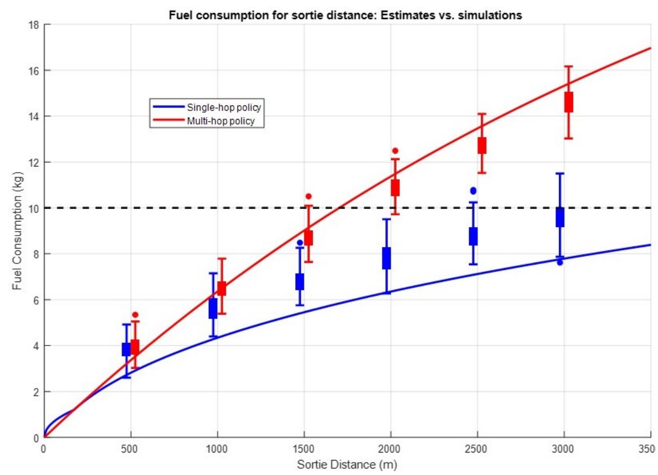

Figure 11. **Fuel consumption vs. sortie distance for1000 Monte carlo simlautions at various sortie distances (box plots), compared to first-order estimates (solid lines).**

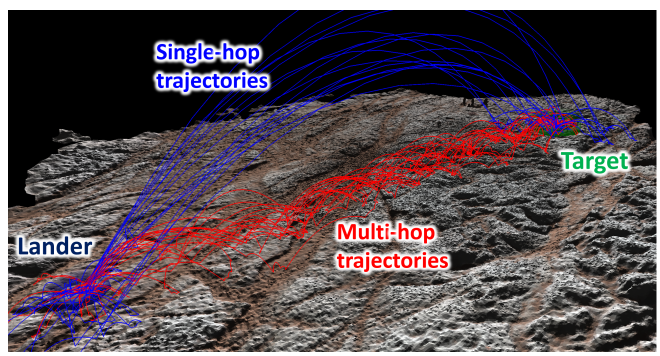

Figure 12. **A sampling of Monte Carlo trajectories for each control policy.**

plots correspond to the maximum, minimum, 25th and 75th percentile fuel cost for each sortie distance. The solid lines correspond to the first order prediction for each control policy (i.e., no control errors or bouncing). As expected, the landing errors induced due to control errors and bouncing require corrective hops for the single-hop policy, resulting is slightly increased fuel consumption for a given sortie distance (about 20%). On the other hand, the simulated multi-hop sorties actually outperform the first-order predictions (i.e., reduced fuel usage), likely due to the fact that the bounces, on average, yield forward progress. Overall, with 10 kg of fuel, these results suggest that SPARROW has a maximum range (with a 90% success rate) of about 1.6 km for the multi-hop control policy and 2.5 km for the single-hop policy.

Localization— Effective operational use of SPARROW requires accurate localization at various stages of an observation campaign. While it is proximal to an serviced by the lander, SPARROW must decide on a reference trajectory that will, in expectation, convey it to the first of possibly several remote regions, depending on the chosen control architecture. Tracking this reference trajectory requires determination of an initial pose relative to the lander and servoing, via low-thrust "jogging", to a required initial attitude cone. Uncertainty in achieving this initial pose is, in reality, convolved with the process noise sources of the thrusting mechanism, including propellant contaminants, flow asymmetries, and unqualified propellant-ground effects. Although the commanded thrust profile can be used to provide a reasonable prior on the initial speed at the start of an arc, data collected during flight – for example, high-speed visual odometry – can be used to reduce uncertainty in estimated linear and angular velocities. Other odometric measurement modalities, including lidar and ground-penetrating radar, were deemed during this study to be less likely to achieve uncertainty reduction under the stringent mass/volume/computation budgets and under the Europan environmental conditions. Star trackers, while amenable to surface pose-estimation, can only lock onto the star field at very slow slew rates. Thus, they are likely to be unsuitable for in-flight attitude estimation.

A narrow band around the reference trajectory yields a region of potential "first ground impact," contact with which would trigger a series of bounces if the impact velocity is sufficiently high. We assume here that the single-hop architecture, owing to retrothrusting, would have comparably low pose knowledge drift due to bouncing, and consequently the next immediate localization requirement comes at the retrothrust stage. Scheduling of retrothrusts is dependent on timing, altimetry, and velocity estimation to achieve standoff and landing at desired speeds. As part of this trade study, we have proposed using a fusion of IMU tilt and three-axis laser altimetry to estimate pose and twist relative to a ground plane and advancing through the retrothrust state machine.

However, under the multi-hop architecture, an intermediate pose estimate following bouncing is needed to decide on the next hop plan. Unfortunately, we have determined, based on specifications of available sensing packages, that no modality is likely to be sufficient for estimation translation during bouncing. We therefore propose that this pose estimate instead be generated following settling via a longer integration modality as used at the final remote sight, discussed below.

Localization at remote regions is crucial for spatially registering science products, though the pointing requirements during science activities are far less stringent. At such remote regions, we propose to use star trackers for approximating position on Europa's surface relative to the lander. Perturbation of the SPARROW attitude at the remote sight may be informative for disambiguating yaw, though this remains challeging. However, the greatest localization challenge comes with the inbound flights needed to return SPARROW to the lander, as poor planning, estimation, or tracking can result in risk to the lander and to the SPARROW infrastructure. As yet, a localization refinement strategy has not been identified for this use case. Some options are being explored now for performing lander-relative localization at elevation prior to initiating a return arc. Although there remain considerable observability issues with range-based localization, an examination of potential navigation aids will be conducted in Phase II to better robustify the feasibility and economy of the lander-return facet of this concept.

7. SUMMARY AND FUTURE WORK

This paper has discussed the scientific impetus behind the exploration of Europa via a mobile asset. A science traceability matrix was summarized and the effect of sortie range discussed. Challenges of more traditional modes of locomotion were detailed alongside a justification for the use of propulsive hoppers as terrain-agnostic options. The results of first-order calculations regarding the energetics and efficacy of five propulsion architectures were provided and showed two, hot water and an electrolyzed hydrogen and water bi-propellant, to be among the most promising. Finally a discussion of control and observability strategies that may be employed in the tracking of reference trajectories and correcting discrepancies between desired and observed landing locations was given.

In the remainder of this Phase I study, to end in February of 2019, calculations shall be performed with less-idealized assumptions. A hot-water thruster is currently under development and shall be tested inside a vacuum chamber to attain a representative thrust profile, which may then be used to refine control uncertainty during *hops*. The EDuS prototype will be expanded upon and tested for power consumption, excavation rate, and energy per kg of sample transferred. Additionally, the challenge of nozzle and cage icing in cold environments shall be addressed. Water thruster firings of the NASA Optical Communications and Sensor Demonstration Program (OCSDP), both during ground-based testing and on-orbit, exhibit excessive icing due to the rapid cooling of exhaust gases. This phenomenon will be explored as part of this task, as well as the viability of nozzle heating, as was found to be sufficient during the OCSDP program [RJC+18].

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REFERENCES

[Ash16] Yosef Ashkenazy. The surface temperature of europa. *Physica A*, 2016.

[BG88] B. Buratti and M. Golombeck. Geologic implications of spectrophotometric measurements of europa. *Icarus*, 75:437–449, 1988.

[CCD+09] R. Carlson, W. Calvin, J. Dalton, G. Hansen, R. Hudson, R. Johnson, T. McCord, and J. Moore. *Europa*. University of Arizona Press, 2009.

[Dog07] et al Doggett, T. Global geologic map of europa. In *Proceedings of the 38th Lunar and Planetary Science Conference*, 2007.

[Dud] From a source of heat comes the power to explore. https://rps.nasa.gov/technology/. Accessed: 2018-07-30.

[ea05] G. Hansen et al. Ice grain size distribution: Differences between jovian and saturnian icy satellites from galileo and cassini measurements. *Bulletin of the American Astronomical Society*,

37:729, 2005.

[ea11] Steven Squyres et al. Visions and voyages for planetary science in the decade 2013-2022. Technical Report 1, National Research Council, USA, 2011.

[ea16] Kevin Hand et al. Europa lander study 2016 report. Technical Report 1, NASA Jet Propulsion Laboratory, Pasadena, CA, USA, 2016.

[FW15] D. Floreano and R. Wood. Science, technology and the future of small autonomous drones. *Nature*, 521:460–466, 2015.

[JBF+17] K. James, M. Bodnar, M. Freedman, L. Osborne, R. Grist, and R. Hoyt. Hydros: High performance water-electrolysis propulsion for cubesats and microsats. In *IEEE Space Conference*, 2017.

[KPA+04] M. Kolditz, N. Pilz, H. Adirim, P. Rudloff, M. Gorsch, and M. Kron. Overview of current hot water propulsion activities at berlin university of technology. In *2nd International Conference on Green Propellants for Space Propulsion*, 2004.

[KS14] Arash Kalantari and Matthew Spenko. Modeling and performance assessment of the hytaq, a hybrid terrestrial/aerial quadrotor. *IEEE Transactions on Robotics*, 30:1278–1285, 2014.

[LCN] D. Lee, Y. Cheng, and H. Nayar. Indirect and direct planetary illumination modelling for robotic surface exploration sensing.

[MBB+09] J. Moore, G. Black, B. Buratti, C. Phillips, J. Spencer, and R. Sullivan. *Europa*. University of Arizona Press, 2009.

[MHHS89] E. Morren, S. Hay, T. Haag, and J. Sovey. Performance characterization of an engineering model multipropellant resistojet. *Journal of Propulsion*, 5, 1989.

[Mor05] D. Morrison. *Planetary Satellites*. University of Arizona Press, 2005.

[NHP18] T. Nordheim, K. Hand, and C. Paranicas. Preservation of potential biosignatures in the shallow subsurface of europa. *Nature - Astronomy*, 2:673–679, 2018.

[PCG+09] C. Paranicas, J. Cooper, H. Garrett, R. Johnson, and S. Sturner. *Europa*. University of Arizona Press, 2009.

[PSE71] K. Pugmire, R. Shaw, and G. Enos. Applied resistojet technology. *Journal of Spacecraft*, 8, 1971.

[RJC+18] D. Rowen, S. Janson, C. Coffman, R. Welle, D. Hinkley, B. Hardy, and J. Gangestad. The nasa optical communications and sensor demonstration program: Proximity operations. In *32nd Annual AIAA/USU Conference on Small Satellites*, Logan, UT, USA, 2018.

[SW14] W. Sun and Z. Wei. Numerical analysis of the flow field in the nozzle of hot water rocket motor. In *Advanced Materials Research ISSN: 1662-8985*, 2014.

[Zac18] K. Zacny. *Outer Solar System*. Springer, 2018.

BIOGRAPHY

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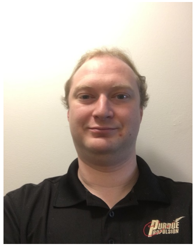

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